Production-Ready 4 kHz ArF Laser for 193 nm Lithography

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Abstract

Semiconductor chip manufacturing is on the verge of a new production process node driving critical feature sizes below 100 nm. The next generation of 193 nm Argon Fluoride laser, the NanoLith™ 7000, has been developed in response to this recent technology development in the lithography industry. The NanoLith™ 7000, offering 20 Watts average output power at 4 kHz repetition rate, is designed to support the highest exposure tool scan speeds for maximum productivity and wafer throughput. Technology improvements to support the move from pilot production to full production will be described. With core technology defined and performance to specification established, attention turns to cost of operation, which is closely tied to module lifetime and reliability. Here we present results of the NanoLith™ 7000 system lifetest tracking all optical performance data over a 4.4 Billion shot. The system is operated in firing modes ranging from 1-4 kHz, and up to 75% duty cycle. Overall system performance measured to date both in the lab and in the field suggests that this laser meets all the production requirements for 193 nm lithography.

1. Introduction

In 2001, Cymer introduced to the semiconductor capital equipment market a 4 kHz 20 W Argon Fluoride laser, the NanoLith™ 7000, as the primary light source for 193 nm optical microlithography. This new generation of lithography tools presents a tremendous technical challenge not only in terms of performance specification but also in terms of lifetime and reliability. In order to meet the strict requirements of the new generation 193 nm lithography technology, the NanoLith™ 7000 has been completely redesigned from the previous generation of ArF lasers. Every major module, including the discharge chamber, the line narrowing module, the wavelength stabilization module, and the pulse power system, has been upgraded or modified. The performance of the NanoLith™ 7000 has already been presented in a previous SPIE Microlithograpy Conference.[1,2] With the system performance established to meet the specification requirements the system development is complete only when the lifetime requirement is properly addressed. Here we present the results of the NanoLith™ 7000 lifetest. Among the system level performance parameters the key parameters to be discussed are energy/dose performance, discharge voltage trend, wavelength stability, and bandwidth change over the system lifetime.

2. The NanoLith™ 7000 System Configuration

2.1. Discharge Chamber

The NanoLith™ 7000 discharge chamber was fundamentally redesigned as compared to previous chamber designs. The geometry of the tangential fan has been optimized to support higher gas velocities at roughly the same fan speeds as in previous Krypton Fluoride and Argon Fluoride laser models. The improved flow loop yields better flow stability and uniformity of the gas flow across the discharge gap. Additional heat exchangers have been added to maintain proper gas temperatures under the increased thermal load at high repetition rates and duty cycles (up to 4kHz, 75%DC). Various additional changes to internal chamber architecture have been introduced to improve uniformity of the laser gain and output energy stability across

all repetition rates. A new electrode design implemented in the NanoLith™ provides better chamber efficiency and energy stability as well as extending chamber life.

The higher energy loads at 4kHz operation resulted in a significant increase in the chamber cross section and subsequently its weight. As a result the gas volume is increased by ~1.96 times. The increased volume of the laser-active media extends the gas life to greater than 100 million shots, compared to 50M shots for previous ArF models.

2.2. Pulse Power System

The pulse power system has also undergone major changes from previous designs. The most evident of these is the addition of a new module, the resonant charger, as an intermediary stage between the high voltage power supply and the commutator. The primary advantage of this technology is its scalability to higher repetition rates. With increasing repetition rates, the time between laser pulses —and hence the time permitted for charging the primary capacitor, C_0— decreases. In fact, the allotted charging time decreases faster than the interpulse time because some interpulse time must be reserved for tasks such as: measuring energy and executing the energy control algorithm. In the traditional, charge-on-command scheme the need for faster charging must be met by redesign of the supply for faster charging or ganging several supplies. In the resonant charger approach, faster charging can be accomplished by reducing the charging inductor and increasing the peak current of the simpler DC supply.

2.3. Line Narrowing Module

The NanoLith™ 7000's line-narrowing module (LNM) contains a couple of major enhancements. First, the optical design has been revised to produce significantly higher dispersion to meet the stringent bandwidth requirements imposed by today's high NA scanners. Second, this module incorporates a fast and precise PZT-based tuning element to supplement the stepper motor used in prior designs.[3] This two-level wavelength control provides greatly improved line center stability in a wide range of repetition rates and with much faster response time. This gain in linecenter performance translates directly to enhanced focus control on the wafer.

2.4. Wavelength Stabilization Module

The complement to the LNM is the wavelength stabilization module (WSM), which supplies pulse-to-pulse on-board metrology of the output energy, center wavelength and FWHM bandwidth. Meeting pulse–to-pulse control requirements at 4 kHz operation drove a complete redesign of the electronics assemblies within the stabilization package, including a new faster microprocessor.

Drive electronics and a new wavelength-control algorithm have been added to support the high-speed tuning element in the LNM. Improved algorithms for calculating wavelength combined with a more accurate calibration procedure, yield a significant improvement in wavelength tuning accuracy for the system. The optical design of the WSM module in the NanoLith™ 7000 is similar to the one in the 5000A and 6000A series, although a number of engineering improvements will result in longer module life and better long term stability.

2.5. Enclosure

The space requirement of new semiconductor equipment is usually an important figure in the budget planning and operating cost analysis for new wafer Fabs. With the NanoLith™ 7000 Cymer has been able to double the system performance without a significant increase in its dimensions or service area compared to today's ELS-

6000 lasers. Effectively, the footprint is unchanged while the height has been increased by 7 inches to accommodate the new pulsed power modules. Convenient door panels provide easy service access to enable gas service and maximum uptime. The NanoLith™ 7000 is in compliance under the newest SEMI Standards (S2-0200).

3. Test Procedures

The test was conducted as a series of gas tests. Various engineering tests, which were intended to test the performance of specific modules, were conducted in between the gas tests. Three different firing modes, representing three duty cycle ranges, were used for the gas test. Mode 1: 1000 Hz, 10% duty cycle. Mode 2: 4000 Hz, 30 % duty cycle. Mode 3: 4000 Hz, 75 % duty cycle. The gas test firing sequence was mode 1, mode 2, mode 3, mode 2, and back to mode 1. The majority of shot counts were accumulated in high duty cycle mode, mode 3. During the gas test the energy was fixed at 5 mJ.

4. Lifetime Performance

4.1. Energy Performance

As the shot counts accumulate on a system, the system performance degrades due to various causes. Electrode erosion, reduction in the grating reflectivity, transmittance change of various optical elements, output coupler reflectance change, etc., are some of the major causes of system degradation with aging. System degradation is most clearly seen in the conversion efficiency from electrical to optical energy. Often this efficiency change is the most critical lifetime limiting factor in excimer lasers. Since C0 is the primary capacitor for energy storage in the NanoLith™ 7000, the voltage across C0, V_{C0}, is a primary indicator of electric energy delivered to the discharge chamber to produce the required optical output. Hence output energy, E, vs the voltage across C0, V_{C0}, is the main indicator of system energy efficiency.

Fig. 1 shows the evolution of output energy vs voltage across the primary capacitor, V_{C0}, with the system shot count. the NanoLith™ 7000 pulse power system can take up to V_{C0} = 1200 V. This means that the upper limit for average V_{C0} should be about 1150V considering some operational margin. Fig. 1 shows that at the nominal operating energy of 5 mJ, there has been less than 150 V increase in V_{C0} in 4.4 Billion shots. Therefore the average voltage rise rate is ~ 35 V/Bshots. By projecting this rate of V_{C0} rise we can estimate the lifetime of the NanoLith™ 7000 should be much greater than 6 B shots.

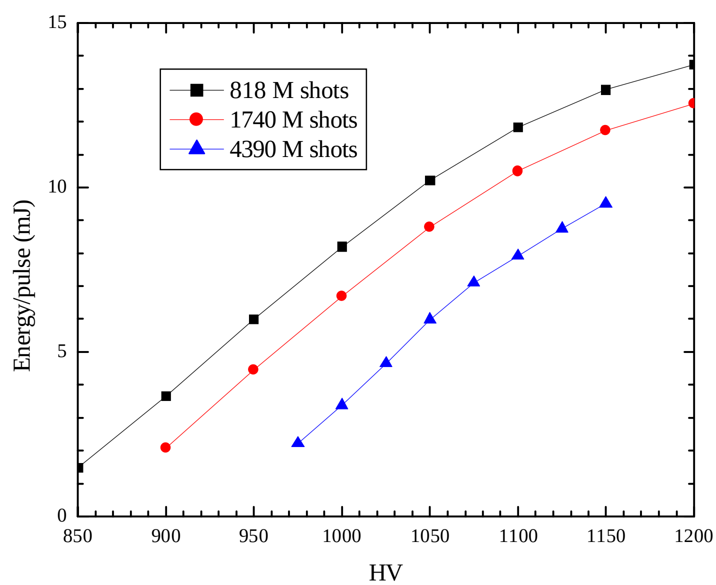

Fig. 1. Evolution of output energy vs voltage across C0. The measurement was done at 4 kHz operation.

Another important implication of Fig. 1 is that Energy vs V_{C0} curve is quite linear at 5 mJ up to 4.4 B shots and is expected to stay linear up to 6 B shots. This linearity between energy and applied voltage is a critical component in ensuring the proper operation of energy control algorithm. The linearity seen in Fig. 1 suggests that the NanoLith™ 7000 should maintain optimum energy control to the end of its system life.

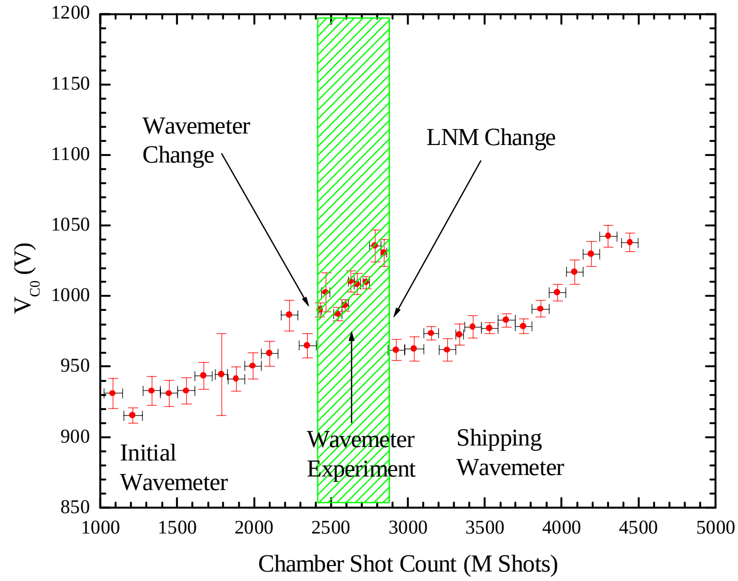

Fig. 2. Evolution of average V_{C0} during the gas test.

Fig. 2 shows the evolution of average V_{C0} during the lifetest. Each data point is the average of V_{C0} for each gas test. The vertical error bars are the standard deviation of the V_{C0} distribution and the horizontal error bars represents the range of shot counts for each test. Typically, the standard deviation was about 10V. At ~1800 M shots, the standard deviation was about twice as large. This was because the gas test was run with F2 injection turned off accidentally during the entire gas cycle. At 2.3 B shots the wavemeter was changed to conduct a series of experiments aimed at improving wavemeter performance. At the end of the experiments the wavemeter configuration was finalized and the LNP was replaced.

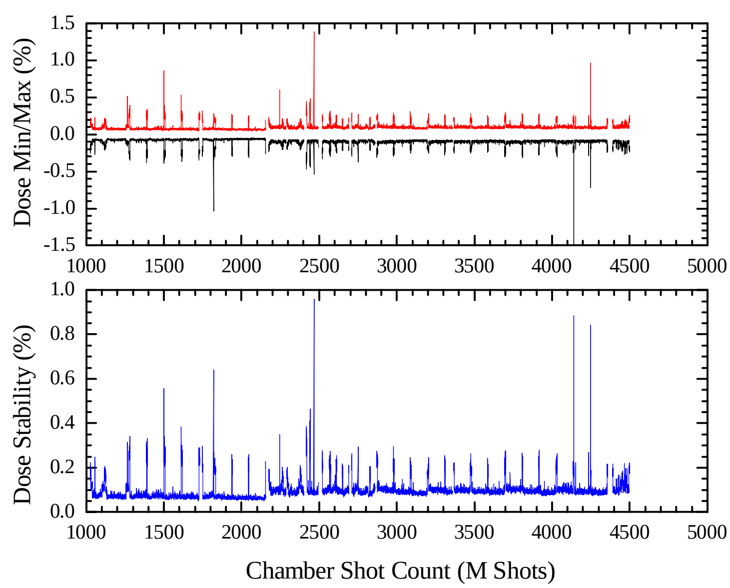

Fig. 3. Dose Error over lifetime.

Dose stability is of great importance for lithography application. The dose performance of the NanoLith™ 7000 has been discussed in the previous papers.[1,2] In Fig. 3 we present the consistency of the NanoLith™ 7000 dose performance throughout its lifetime. By applying 99.7% criteria most of the dose spikes should be eliminated. However, even after applying 99.7% criteria, there clearly is an identifiable pattern in the dose performance per gas test cycle. The NanoLith™ 7000 is specially designed for optimum performance at high repetition rate. The dose pattern per gas cycle shown in Fig. 3 is the consequence of this high repetition rate optimization. As described in the

previous section, each gas cycle started and ended with mode 1, 1000 Hz 10 % duty cycle run and most of the shot counts were accumulated in mode 3, 4000 Hz, 75 % duty cycle run. During the 4000 Hz run the dose error is about 0.1 %. During the 1000 Hz run the dose error increases, but is still less than 0.3 % after applying 99.7% criteria. This change in dose error relative to the mode changes resulted in the dose error pattern shown in Fig. 3.

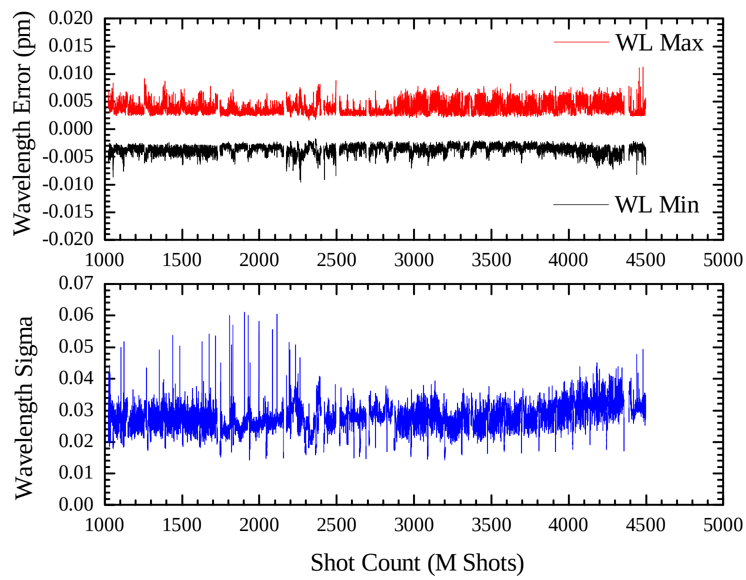

Fig. 4. Evolution of wavelength error.

4.2. Linecenter Error

As discussed in the previous papers the NanoLith™ 7000 employs dual wavelength control mechanism, stepper motor and piezoelectric transducer. The performance of this dual system wavelength control has already been presented earlier.[1,2] Fig. 4 shows the lifetime performance of the NanoLith™ 7000 wavelength control. The figure shows that the NanoLith™ 7000 can maintain the wavelength error to less than 0.01 pm throughout its lifetime. It is not only an illustration of how precise the control mechanism is but also a demonstration of the robustness of the control system. Throughout the various wavemeter experiments and LNM change the wavelength error was controlled with near perfection.

4.3. Linewidth

The linewidth measured by the laser is shown in Fig. 5. Due to various experiments with the wavemeter the linewidth reading did not show optimum performance. Throughout this experimental period the spectral performance of the laser was also monitored using an ELIAS Echelle spectrometer[4] and the results are shown in Fig. 6. In Fig. 6 the

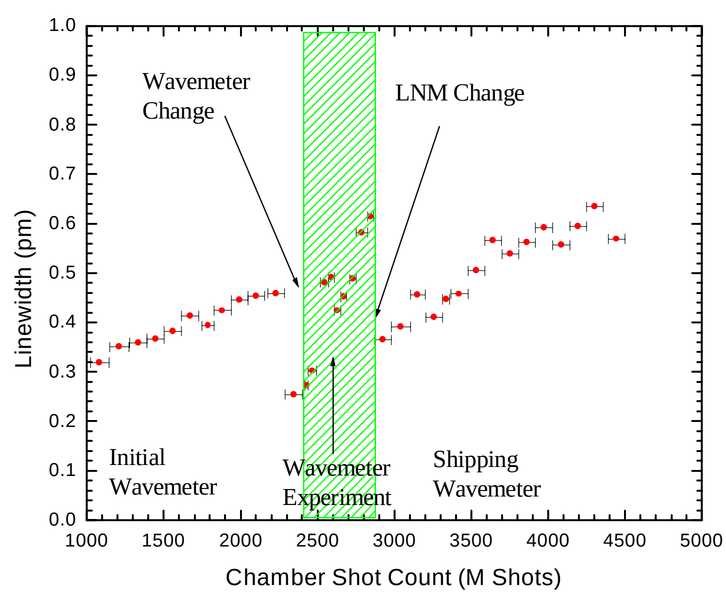

Fig. 5. Linewidth during the lifetest.

deconvolved FWHM of the NanoLith™ 7000 measured with an ELIAS Echelle spectrometer is shown as a function of the repetition rate at various stages of system life. One can immediately identify a large structure at about 3300 Hz. This structure is believed to be due to resonant build-up of acoustic pressure wave in the discharge chamber. Except the resonant spikes, the baseline linewidth was less than 0.35 pm at the beginning of the lifetest. As the system ages, the baseline slowly increased to more than 0.35 pm. However the resonant spike signature and the peak height of the spikes had hardly changed.

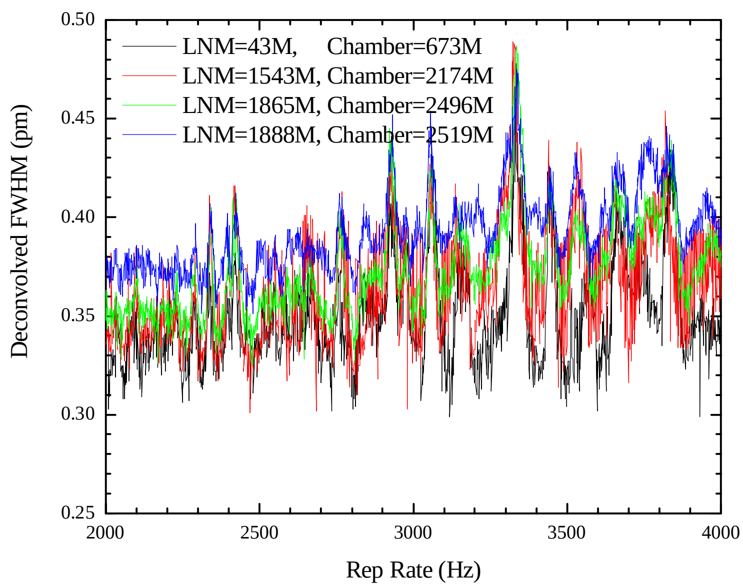

Fig. 6. Linewidth of the NanoLith™ 7000 as a function of the laser repetition rate measured during the lifetest.

Fig. 7 shows the evolution of spectrum during the system life. All the spectra in Fig. 7 were taken during 4000 Hz operation. The deconvolved FWHM and 95% energy integral linewidth for these spectra are summarized in Table 1. The table shows that the FWHM increased by .025 pm/B shots, while the 95% energy integral increased by 0.1 pm/B shots.

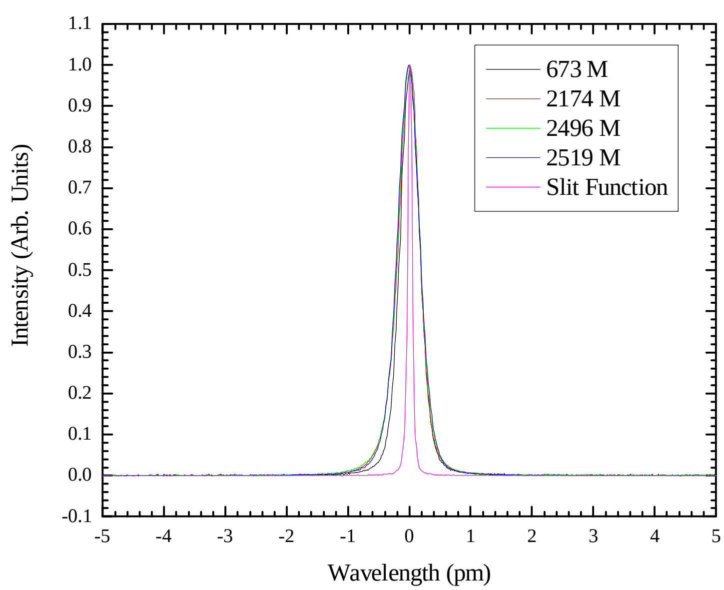

Fig. 7. Comparison of spectra during the lifetest. The spectra were taken at 4000 Hz operation.

Shot Counts	FWHM (pm)	95 % Energy Integral (pm)
673 M	0.34	0.72
2174 M	0.37	0.91
2496 M	0.38	0.96
2516 M	0.39	0.88

Table 1. Deconvolved FWHM and 95 % energy integral for the spectra shown in Fig. 7

4.4. Beam Profiles

Fig. 8 shows the evolution of horizontal and vertical profiles of the NanoLith™ 7000 during the lifetest. The figure shows there is hardly any degradation in the profile in 4 B shots.

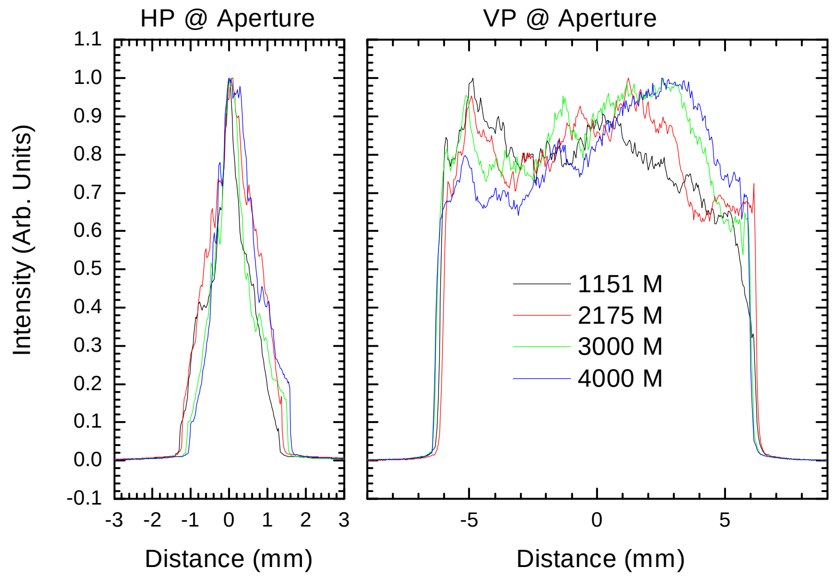

Fig. 8. Evolution of horizontal and vertical profiles during the lifetest.

5. Conclusion and Summary

The output energy vs applied voltage curve showed that the expected system lifetime is much greater than 6 B shots. The laser linewidth consideration showed that the system lifetime should be about 6 B shots. The dose error and linewidth error data showed that the NanoLith™ 7000 would maintain its performance requirements throughout the system lifetime.

By being able to meet the strict requirement throughout its system life, the NanoLith™ 7000 has clearly demonstrated its capability to support 193 nm lithography on a full production scale. This laser is today already powering the next generation of sub 100 nm semiconductor production.

6. Reference

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